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Determination of Standard Response Spectra and Effective Peak Ground Accelerations for Seismic Design and Evaluation

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PURPOSE: The purpose of this Coastal and Hydraulics Engineering Technical Note (CHETN) is to demonstrate the use of DEQAS-R, a computer software program developed by Yule et al. (2005) to generate standard acceleration response spectra and effective peak ground accelerations for seismic design and evaluation of structural features of projects under the responsibility of the U.S. Army Corps of Engineers (USACE).

BACKGROUND: Standard acceleration response spectra and effective peak ground accelerations are needed in the early stages of project development since they can be used as a starting point for preliminary seismic designs and evaluations and determining the need for more refined analyses.

Effective Peak Ground Acceleration. The peak ground acceleration (PGA) is the maximum amplitude of the ground acceleration time-history. In terms of structural response, it corresponds to the peak value of the absolute acceleration of a single degree of freedom (SDOF) system with infinite stiffness, that is, with a natural period of vibration equal to zero. This parameter does not necessarily provide a complete representation of the severity of the earthquake, in terms of its potential to induce structural damage. Other parameters such as the effective peak acceleration (EPGA) and the effective peak velocity (EPGV) have been proposed as alternatives to quantify the severity of the ground motion. Several definitions and different physical interpretations have been proposed for these parameters, which have been employed to define design ground motions for use in model building codes. They were introduced in the Applied Technology Council (1978) seismic provisions as convenient normalizing factors for construction of design response spectra for ground motions of normal duration. The EPGA was defined as proportional to the spectral ordinates corresponding to periods within the range of 0.1 to 0.5 sec, while the EPGV was defined as proportional to the spectral ordinate corresponding to a period of about 1 sec. The constant of proportionality (for a 5 percent damping spectrum) was set at a standard value of 2.5 in both cases. The EPGA and EPGV are related to peak ground acceleration and peak ground velocity but are not necessarily the same as or directly proportional to peak acceleration and velocity. When high frequencies are present in the ground motion, the EPGA may be significantly less than the peak ground acceleration. In general, if one examines the ratio between the spectral ordinate at period 0.2 sec and the corresponding PGA value at individual locations in the national probabilistic hazard maps, the value of the ratio is variable and generally less than 2.5.

Newmark and Hall (1982) characterized the effective peak acceleration as the acceleration value that is most closely related to structural response and to damage potential of an earthquake. That is, this concept of effective peak acceleration is intended to reflect the actual damage potential of the seismic excitation, which cannot be accurately described only by the peak value of the ground

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acceleration. The definition of the effective peak acceleration therefore must take into account not only the amplitude of the excitation, but also its frequency content and the type and characteristics of the general structural system under consideration.

Standard Response Spectra. A response spectrum is a plot of the peak values of the response (displacement, velocity, or acceleration) of a number of SDOF systems with different natural vibration periods subjected to the same seismic input. Therefore, an acceleration response spectrum represents the peak accelerations that a suite of SDOF systems with a range of natural periods may exhibit when subject to a given ground motion component.

In general, the acceleration response spectrum associated with a specific time-history recorded at a given location has a jagged shape with significant peaks and valleys. The response spectrum for another ground motion recorded at the same site during a different earthquake will exhibit also an irregular shape, but the peaks and valleys will not necessarily coincide with those in the previous one. Therefore, appropriately smoothed spectra are usually defined for design and evaluation purposes. These spectra are termed design response spectra. They do not represent the particular acceleration response from a single ground motion time-history, but rather they are intended to be more representative of general characteristics for a reasonable range of expected ground motions at a given site. There are two basic approaches for the development of design response spectra: site-specific or standard procedures.

Site-specific response spectra are developed using source to site distances, appropriate attenuation relationships, expected magnitudes, and actual local site conditions. Therefore, it is typically assumed that site-specific studies will provide more accurate acceleration spectra than using the codified standard acceleration spectra. Headquarters, U.S. Army Corps of Engineers (1999) describes the conditions requiring a site-specific ground motion study. Site-specific response spectra can be generated by means of a deterministic seismic hazard analysis (DSHA) or a probabilistic seismic hazard analysis (PSHA). In the DSHA, the site ground motions are estimated for a specific earthquake scenario, defined as a seismic event of a certain magnitude for a particular seismic source occurring at a certain distance from the site. The representation of the ground motions in terms of the corresponding site-specific response spectra is achieved by using appropriate attenuation relationships. Information on this approach can be found in HQUSACE (1999). The PSHA is an approach that uses the likelihood (probability) that a given level of ground motion will occur during a specific exposure period. In the PSHA, the site ground motions are defined for selected values of the probability of exceedance in a given time exposure period, or for selected values of annual frequency or return period for ground motion exceedance.

This approach considers all potential earthquake sources that may be significant to the site under consideration. This approach incorporates the frequency of occurrence of earthquakes of different magnitudes on the seismic sources, the uncertainty of the earthquake locations on the sources, and the ground motion attenuation including its uncertainty. HQUSACE (1999) describes the procedures for estimating earthquake ground motions according to this approach.

On the other hand, standard response spectra are based on a general characteristic shape that is defined in terms of estimates of selected ground motion parameters, which can be effective peak ground accelerations or spectral accelerations. HQUSACE (1999) describes the approach proposed

by Newmark and Hall (1982) to develop design response spectra using peak ground motion parameters (peak ground acceleration, velocity and displacement), multiplied by a series of appropriate spectral amplification factors that depend on the damping level.

Seismic Hazard Determination. Over the years, there have been significant changes in the seismic hazards maps and their application to estimate ground shaking hazard levels. Since the 1997 NEHRP provisions, more detailed procedures have been introduced for estimating site-specific design response spectra. Probabilistic seismic hazard information is currently available in the form of maps for peak ground acceleration and spectral ordinates at periods of 0.2 and 1.0 sec, which are available for probabilities of exceedance of 10 percent in 50 years and 2 percent in 50 years. The presented hazard is a mean or best estimate value which in most cases will be approximately close to the median or 50 percent confidence level.

The probability of exceedance represents the chance, expressed as a percentage, that a more severe ground motion will occur within a specified exposure time expressed in number of years. Assuming that the temporal occurrence of the earthquake follows a Poisson process, the probability of exceedance (P_e) in a given exposure time (T_e) is related to the annual probability of exceedance (λ_m) as follows:

$$P_e = 1 - e^{-\lambda_m T_e} \tag{1}$$

The reciprocal of the annual probability of exceedance is the return period ($T_R = 1/\lambda_m$), which represents the average number of years between exceedances. For a given (P_e, T_e) pair, the corresponding return period can be obtained as follows:

$$T_R = -\frac{T_e}{\ln\left(1 - P_e\right)} \tag{2}$$

As an example, an earthquake having a probability of exceedance of 2 percent in 50 years would have a mean return period of 2,475 years, whereas an earthquake having a probability of exceedance of 10 percent in 50 years would have a mean return period of 475 years. Table 1 summarizes the return periods for some of the most common combinations of probabilities of exceedance and exposure time.

Table 1
Approximate Return Periods for Different Probabilities of Exceedance and Exposure Times

Prob. of Exceedance, %	Exposure Time, years	Return Period, years
50	50	72
50	100	144
10	50	475
10	100	949
5	100	1,950
2	50	2,475
1	50	4,975

The U.S. Geological Survey (USGS) National Hazard Mapping Project supported by NEHRP provides the latest peer reviewed and published seismic hazard data for the United States. These data are provided in probabilistic hazard maps and interactive Web-based query for certain ground motion parameters. The current link to this project site is located at the following address: *http://earthquake.usgs.gov/hazmaps/*. However, this could change and it may be necessary to search for the most current Web link.

The available probabilistic maps for downloading or viewing correspond to PGA values and 0.2 sec and 1.0 sec spectral acceleration values for probabilities of exceedance of 10 percent in 50 years and 2 percent in 50 years (approximately return periods of 500 and 2,500 years, respectively). The site also provides an interactive menu where the user can obtain the mapped values for a given location specified by latitude/longitude. Ground motion values for the 48 states have been calculated for a grid spacing of 0.05°. Interpolated values are typically calculated using the four surrounding corner points. For guidance, 0.1° latitude is about 10.9 km (6.8 miles), and 0.1° longitude varies, but for the 48 states is on the order of 9.0 km (5.6 miles). Figures 1 and 2 show the probabilistic maps for the 0.2 and 1-sec spectral acceleration values corresponding to a probability of exceedance of 2 percent in 50 years (Frankel et al. 1996; Frankel et al. 2002).

Due to the availability of the national probabilistic seismic hazard data, it is now possible to provide tools to assist in developing design spectra without the need to manually extract data from maps or to explicitly query the USGS Web site. The computer program DEQAS-R (Yule et al. 2005) was developed to provide the needed seismic hazard data based on the most recent national probabilistic seismic hazard information. For user-specified location and return period, the current version of this program can calculate and display the horizontal and vertical standard spectra based on the procedure provided in this document. In addition, the program can generate the equal hazard spectrum for the location and return period indicated as well as the corresponding seismic hazard curves for

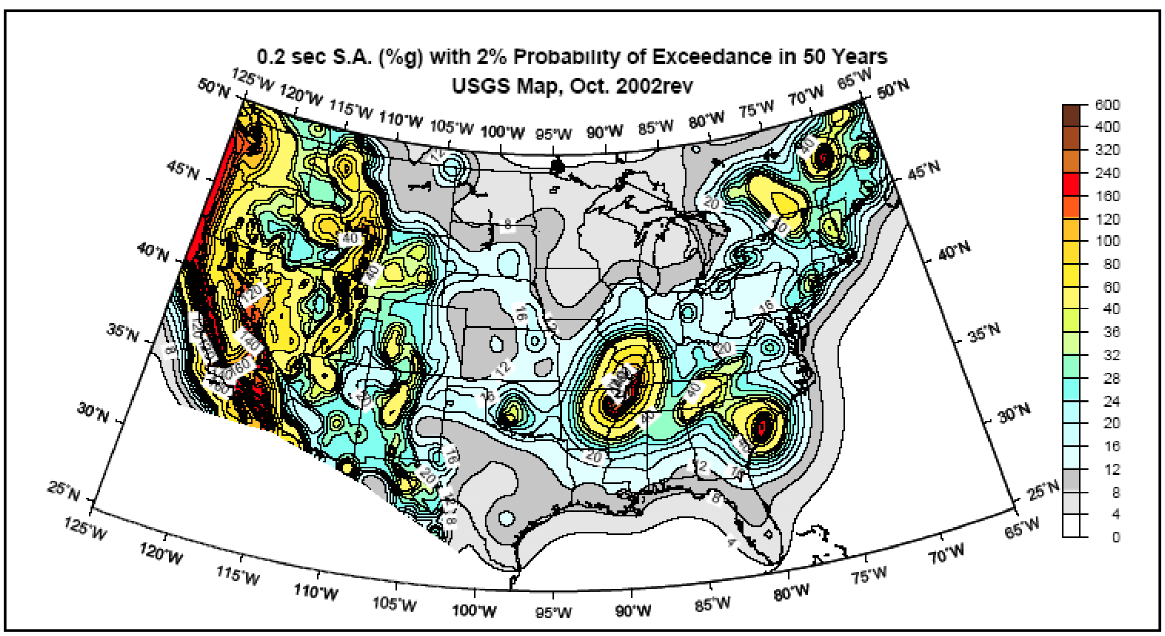


Figure 1. 0.2-sec spectral acceleration with 2 percent probability of exceedance in 50 years

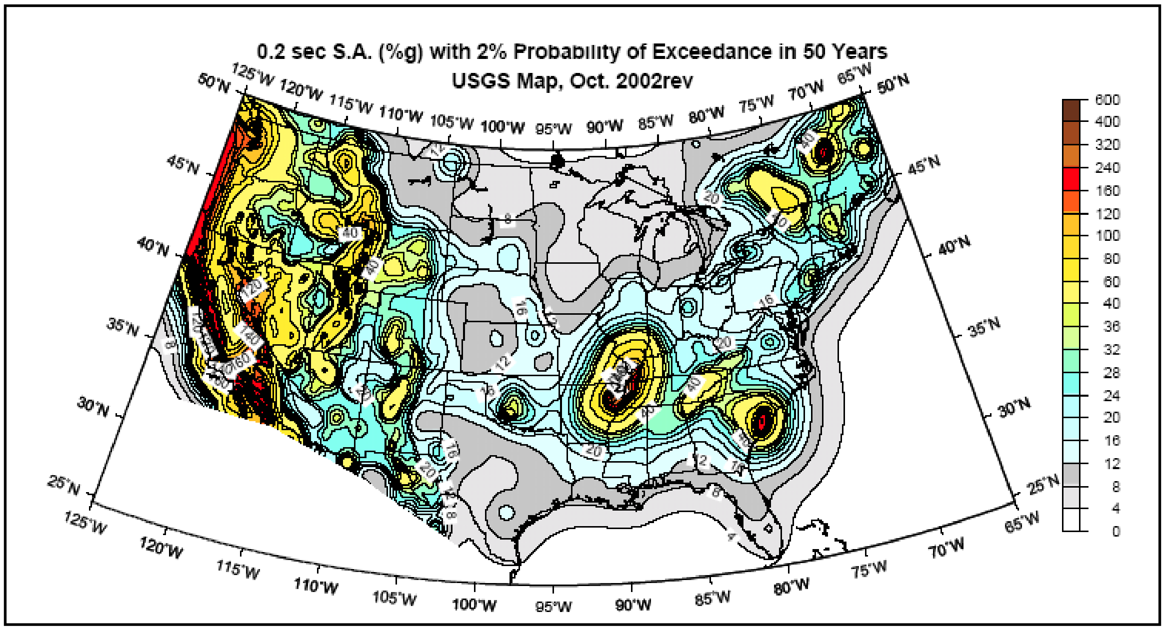


Figure 2. 1-sec spectral acceleration with 2 percent probability of exceedance in 50 years

periods of 0.2 and 1.0 sec. The program also includes additional options to display different maps containing the most recent seismic hazard data. Information on the program DEQAS-R and instructions to request copies of this program can be obtained by requesting information by e-mail to the following address: *dams@erdc.usace.army.mil*.

STANDARD HORIZONTAL SPECTRUM: For a given site location and for a given return period (T_R), the corresponding standard horizontal response spectrum is defined in terms of the spectral ordinates at periods of 0.2 and 1.0 sec, denoted as $S_S^{T_R}$ and $S_1^{T_R}$. The USGS database contains spectral values for a finite number of return periods $\left\{T_R^1, T_R^2, \ldots, T_R^n\right\}$. If a standard spectrum associated with a different probability of exceedance or return period is required, then it is necessary to appropriately modify the available values for S_S and S_1. This is done by assuming that the hazard curves relating the spectral acceleration (S_S) with the return period (T_R) can be approximated by power curve functions of the following form:

$$S_S = b_S \left(T_R\right)^{m_S} \tag{3}$$

This assumption implies that spectral values and return periods are linearly related in a log-log representation, that is:

$$\log\left(S_S\right) = \log\left(b_S\right) + m_S \log\left(T_R\right) \tag{4}$$

The coefficient m_S represents the slope of the straight line and log(b_S) is the intercept on the ordinate axis. For a given return period T_R, then it is possible to identify the two return periods T_R^i

and T_R^{i+1} that define the smallest interval containing T_R, and the corresponding spectral values S_S^i and S_S^{i+1}. Therefore, one can write:

$$\begin{cases} \log(b_S) + m_S \log\left(\mathrm{T_R^i}\right) = -\log\left(\mathrm{S_S^i}\right) \\ \log(b_S) + m_S \log\left(\mathrm{T_R^{i+1}}\right) = -\log\left(\mathrm{S_S^{i+1}}\right) \end{cases} \tag{5}$$

After computing the coefficients m_S and $\log(b_S)$, then it is possible to obtain spectral accelerations at different return periods by this linear log-log interpolation. A similar procedure can be applied for the spectral acceleration S_1.

These spectral values correspond to firm rock conditions. However, the effects of the soil and foundation conditions can greatly affect the structural response, and the standard response spectra must reflect the site characteristics. These site effects are accounted for in the development of the standard response spectra by using two site coefficients F_a and F_v that scale the spectral ordinates to the appropriate values corresponding to the standard conditions A-E as defined in the NHERP provisions. The site coefficients F_a and F_v are determined according to Tables 2 and 3.

Table 2
Site Correction Coefficient F_a

Site Class	Coefficient F_a				
	$S_S \le 0.25$	$S_S = 0.50$	$S_S = 0.75$	$S_S = 1.00$	$S_S = 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.5	1.7	1.2	0.9	0.9

Table 3
Site Correction Coefficient F_v

Site Class	Coefficient F_a				
	$S_1 \le 0.10$	$S_1 = 0.20$	$S_1 = 0.30$	$S_1 = 0.40$	$S_1 = 0.50$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.7	1.6	1.5	1.4	1.3
D	2.4	2.0	1.8	1.6	1.5
E	3.5	3.2	2.8	2.4	2.4

The corrected spectral values are given by:

$$\begin{aligned} \overline{S}_S^{T_R} &= F_a S_S^{T_R} \\ \overline{S}_1^{T_R} &= F_v S_1^{T_R} \end{aligned} \tag{6}$$

The seismic hazard information is based on an inherent structural damping of 5 percent. If spectral values for other damping ratios are required, then the spectral accelerations are adjusted using the correction coefficients B_S and B_1 provided in Table 4.

To determine the standard horizontal response spectrum it is necessary to compute first the values of the two periods defining the interval of maximum spectral amplification. They are denoted as T_0 (start

Table 4
Damping Correction Coefficients B_S and B_1

Damping, %	Coefficient B_S	Coefficient B_1
≤ 2	0.80	0.80
3	0.87	0.87
4	0.93	0.93
5	1.00	1.00
6	1.06	1.04
7	1.12	1.08
8	1.18	1.12
9	1.24	1.16
10	1.30	1.20
20	1.80	1.50

of maximum amplification plateau) and T_S (end of maximum amplification plateau), and they are defined as follows:

$$
\begin{aligned}
T_S &= \frac{B_S \bar{S}_1^{T_R}}{B_1 \bar{S}_S^{T_R}} \\
T_0 &= \frac{1}{5} T_S
\end{aligned}
\tag{7}
$$

The standard horizontal spectrum is then defined as follows:

$$
S_H^{(T_R,\xi)}(T) = \begin{cases} \bar{S}_S^{T_R}\left[\left(\dfrac{5}{B_S}-2\right)\dfrac{T}{T_S}+0.4\right] & \mathit{for}\ 0 \le T < T_0 \\ \dfrac{\bar{S}_S^{T_R}}{B_S} & \mathit{for}\ T_0 \le T < T_S \\ \dfrac{\bar{S}_1^{T_R}}{B_1 T} & \mathit{for}\ T_S \le T \end{cases}
\tag{8}
$$

Example 1: This problem demonstrates the development of a 5 percent damping horizontal standard response spectrum for an Operational Basis Earthquake (OBE). This corresponds to an event with a 50 percent chance of exceedance in 100 years, i.e., a return period of 144 years. The project data are given by:

Name: Mud Mountain Dam
Location: King County, WA
Latitude: 47.1°
Longitude: -121.9°
Site conditions: Soft rock foundation (site class C)

a. Start the program (Figure 3).

b. Enter site location and site class (Figure 4).

c. Define return period (Figure 5).

d. Plot horizontal standard spectrum (Figure 6).

It is also possible to display the 0.2- and 1.0-sec period seismic hazard curves for the specified location. These hazard curves are shown in Figure 7, and they represent the actual seismic hazard data used by the program to compute the spectral values $S_S^{T_R}$ and $S_1^{T_R}$ that were used in the construction of the standard response spectrum. To obtain the values corresponding to the specified return period (e.g., $S_S^{T_R=144}$ and $S_1^{T_R=144}$), the program conducted a linear log-log interpolation using

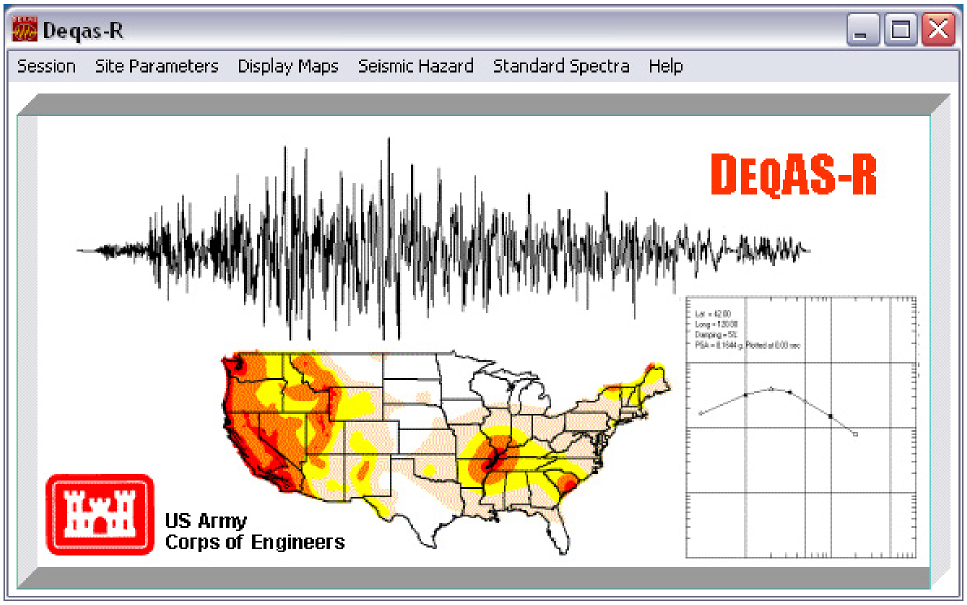


Figure 3. Initial screen

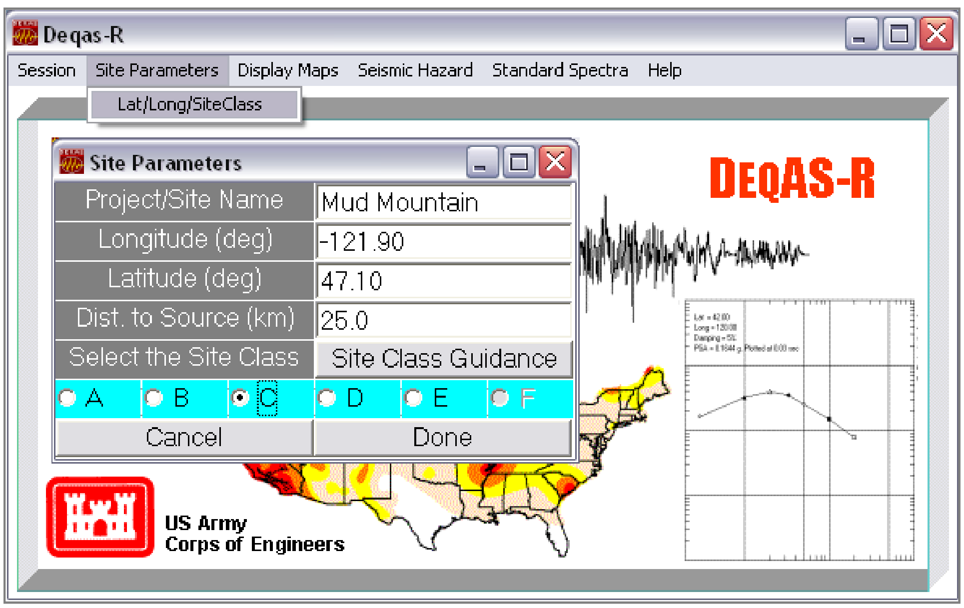


Figure 4. Definition of site parameters for Example 1

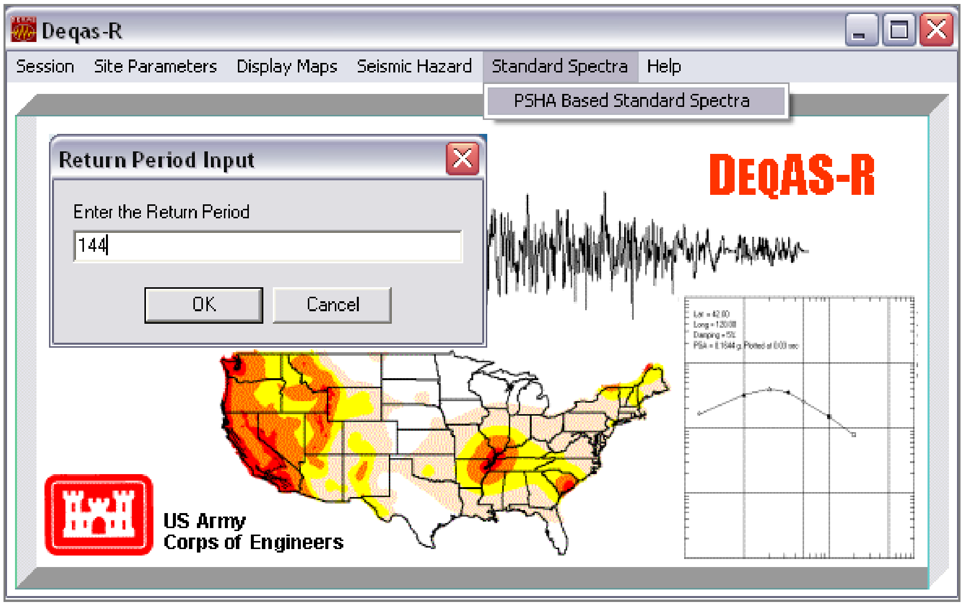


Figure 5. Return period input for Example 1

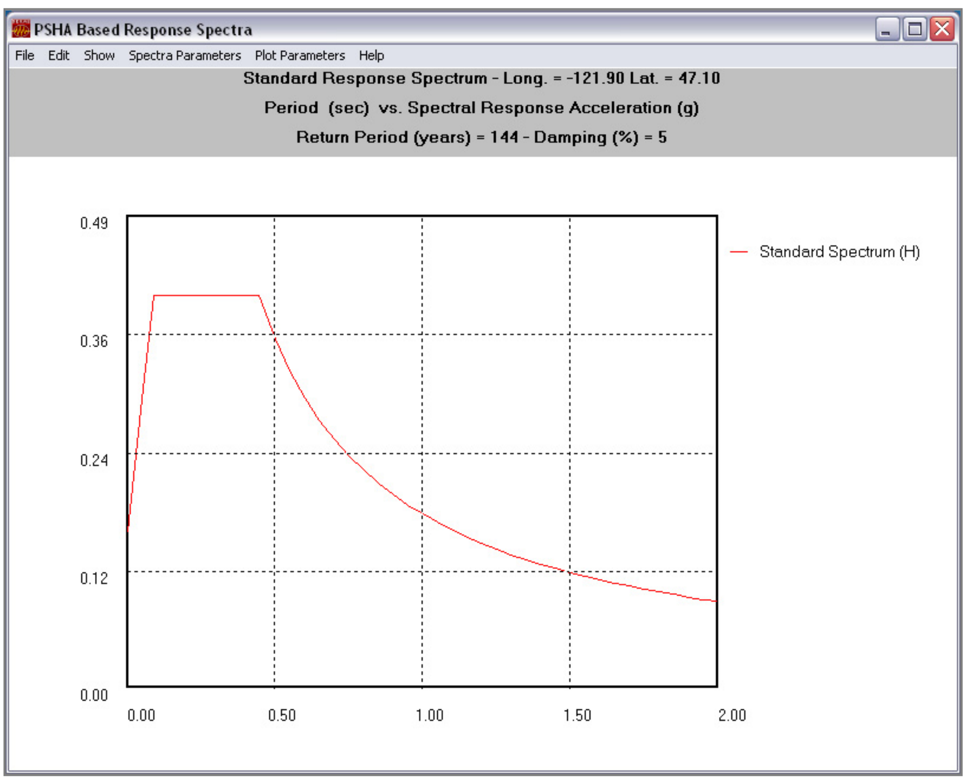


Figure 6. 5 percent-damping standard horizontal acceleration response spectrum for Example 1

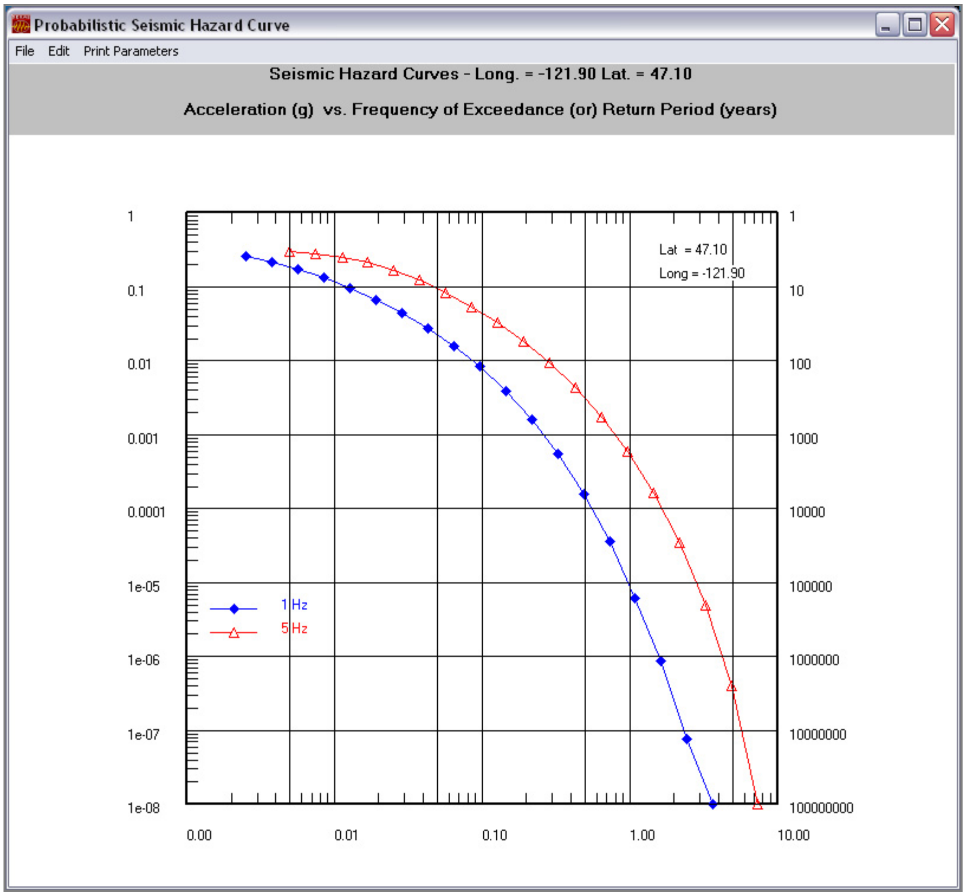


Figure 7. Seismic hazard curves for Example 1

the two closest available values, which for this case correspond to approximate return periods of 120 and 253 years. This is a "local" interpolation scheme, which is adopted to represent a return period interval in the vicinity of the available data points.

STANDARD VERTICAL SPECTRUM: The vertical standard response spectrum is determined based on the source to site distance (R) by means of the factors given in Table 5. These factors were based on the information provided in HQUSACE (1999). In most cases of preliminary design the source-to-site distance will be unknown, and for those cases R = 25 km (15 miles) may be assumed. This general procedure can be applied to both standard and site-specific spectra, although in this last case vertical response spectra can also be derived directly by some attenuation relationships.

Table 5
Conversion Factor F_V

Source to Site Distance, R	Conversion Factor
≤ 10 km	1.00
25 km	0.84
≥ 40 km	0.67

To determine the standard spectrum it is necessary to compute first the period defining the upper limit of the maximum vertical amplification plateau, given by:

$$T_{SV} = \frac{0.67}{F_V} T_S \tag{9}$$

The standard vertical spectrum is then defined as follows:

$$S_V^{(T_R,\xi)}(T) = \begin{cases} F_V \, S_H^{(T_R,\xi)}(T) & for\ T < T_{SV} \\ 0.67 \dfrac{\overline{S}_1^{T_R}}{B_1 T} & for\ T_{SV} \le T \end{cases} \tag{10}$$

Example 2: This problem demonstrates the development of 6 percent damping horizontal and vertical standard response spectra for a Maximum Design Earthquake (MDE) characterized by a return period of 1,000 years. The project data are given by:

Name: Blue River Dam
Location: Lane County, OR
Latitude: 44.2°
Longitude: -122.3°
Site conditions: Rock foundation (site class B)

a. Enter site location and site class (Figure 8).

b. Define return period (Figure 9).

c. Adjust damping level and plot horizontal and vertical response spectra (Figure 10).

EFFECTIVE PEAK GROUND ACCELERATION: For a given return period, the effective peak ground acceleration (EPGA) is determined by dividing by 2.5 the corresponding 5 percent-damping short period spectral acceleration value as follows:

$$\text{EPGA}(T_R) = \frac{\overline{S}_S^{T_R}}{2.5} \tag{11}$$

Example 3: This problem demonstrates the determination of Effective Peak Ground Acceleration (EPGA) values for different return periods (100; 500; 1,000; 2,000; 5,000; and 10,000 years).

Name: Montgomery Point Lock and Dam
Location: AR
Latitude: 33.9°
Longitude: -91.1°
Site conditions: Stiff soil (site class D)

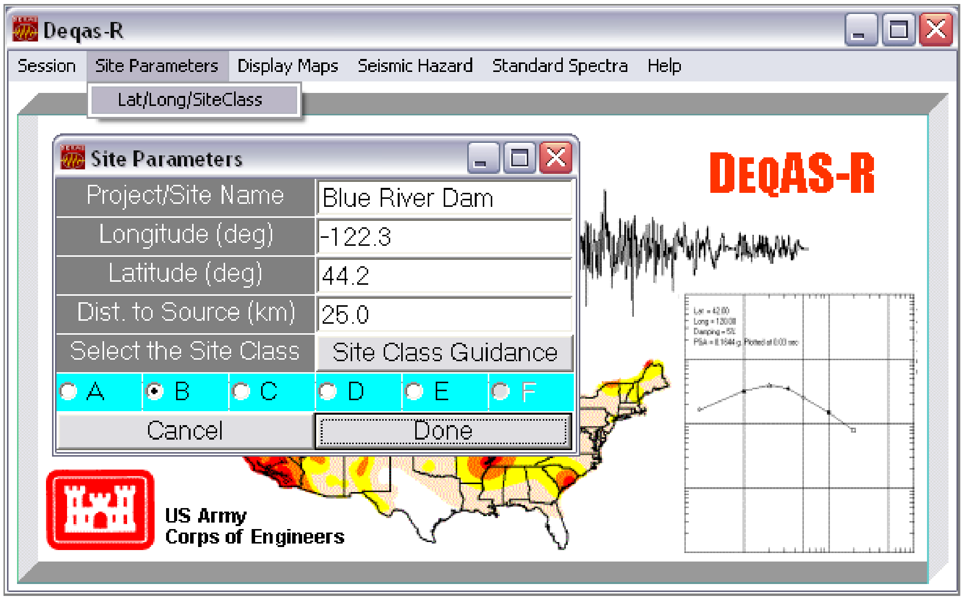


Figure 8. Definition of site parameters for Example 2

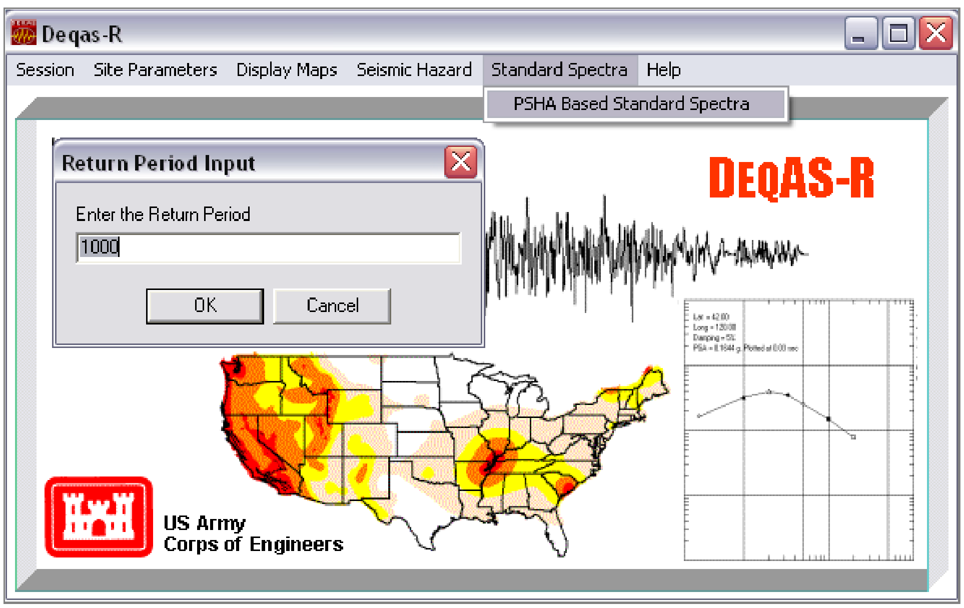
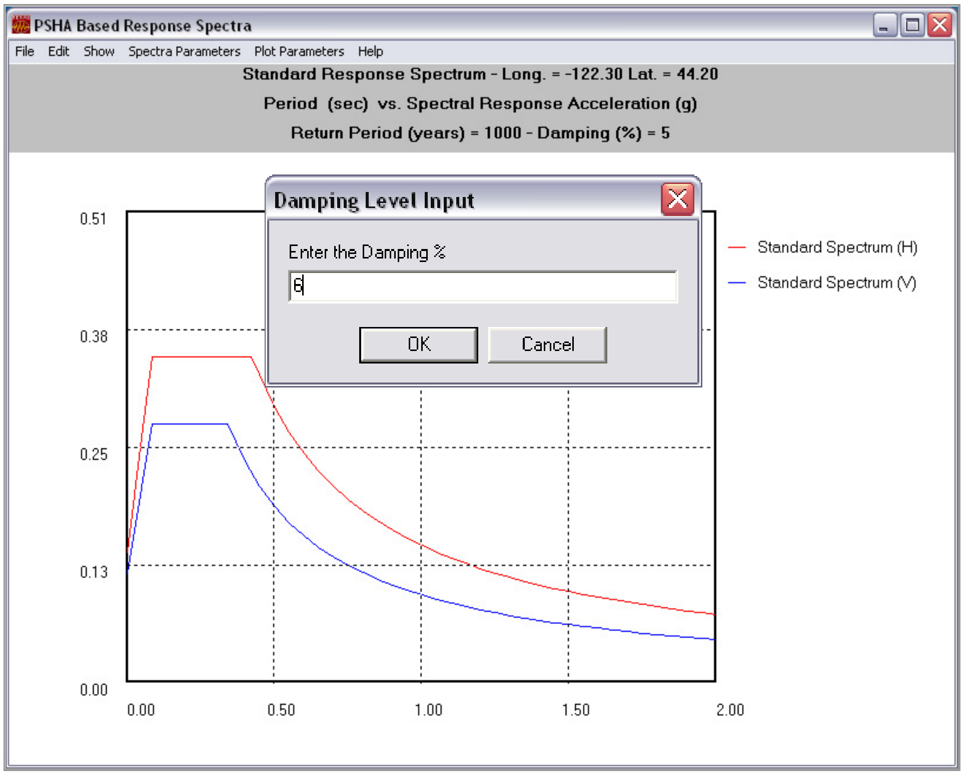


Figure 9. Return period input for Example 2

a. Enter site location and site class (Figure 11).

b. Enter required return periods (Figure 12).

c. Obtain EPGA values (Figure 13).



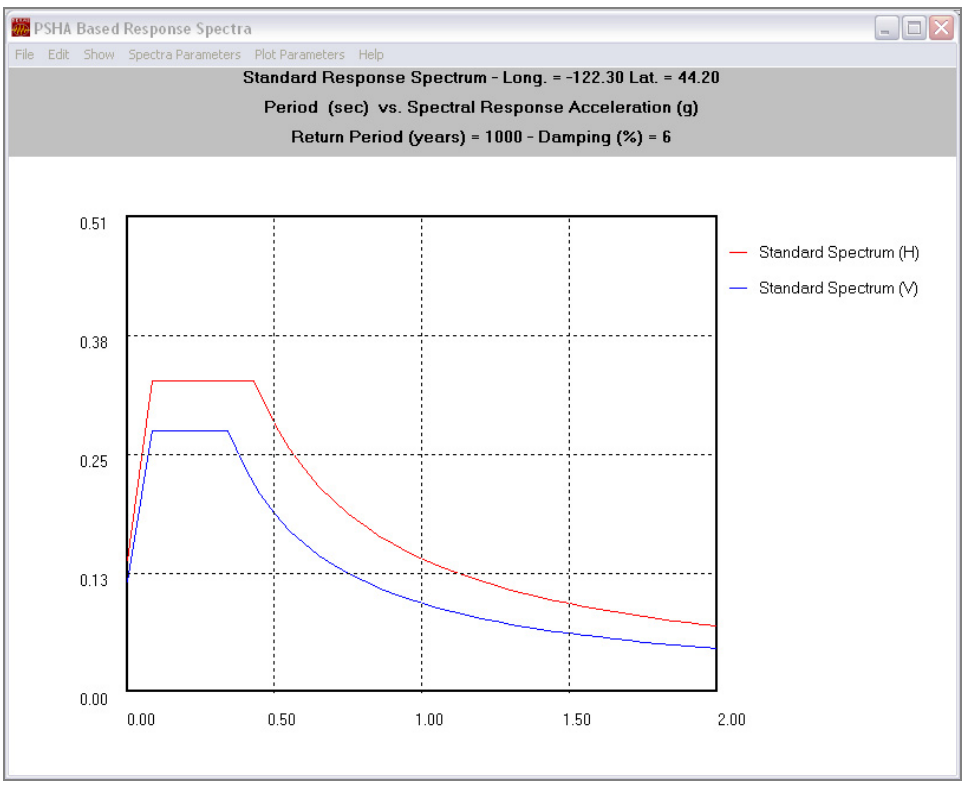


Figure 10. 6 percent-damping standard horizontal and vertical acceleration response spectra for Example 2

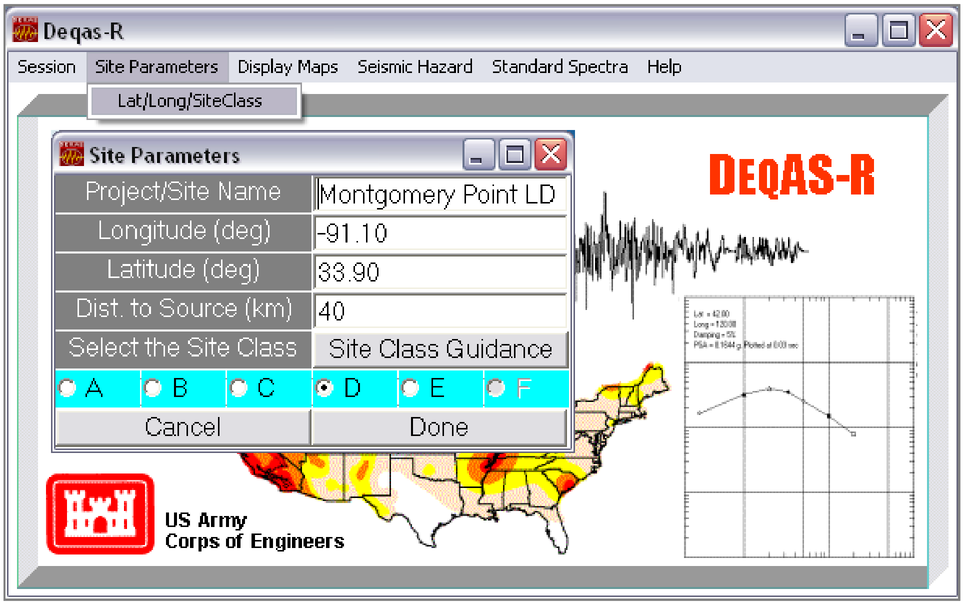


Figure 11. Definition of site parameters for Example 3

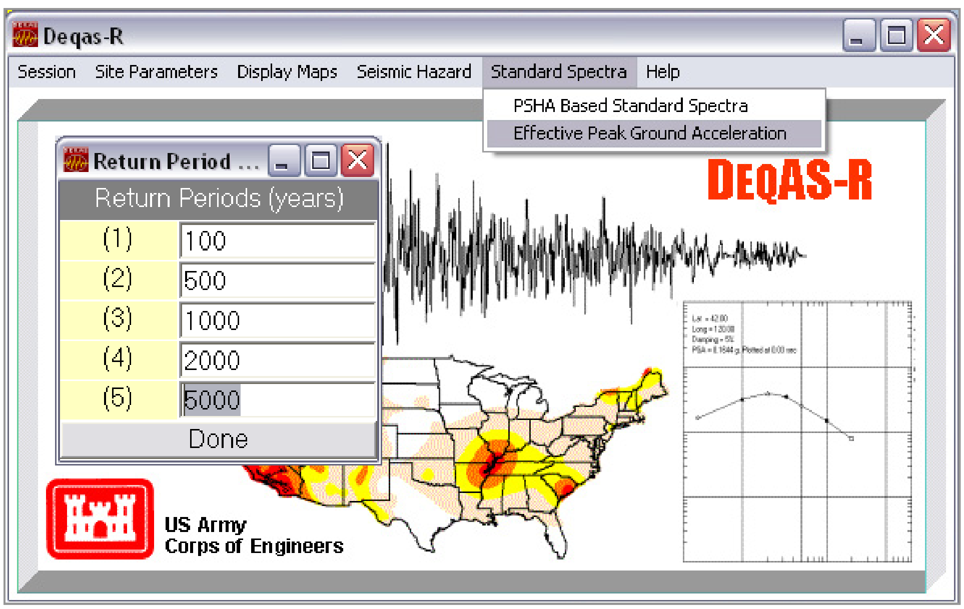


Figure 12. Return period input for Example 3

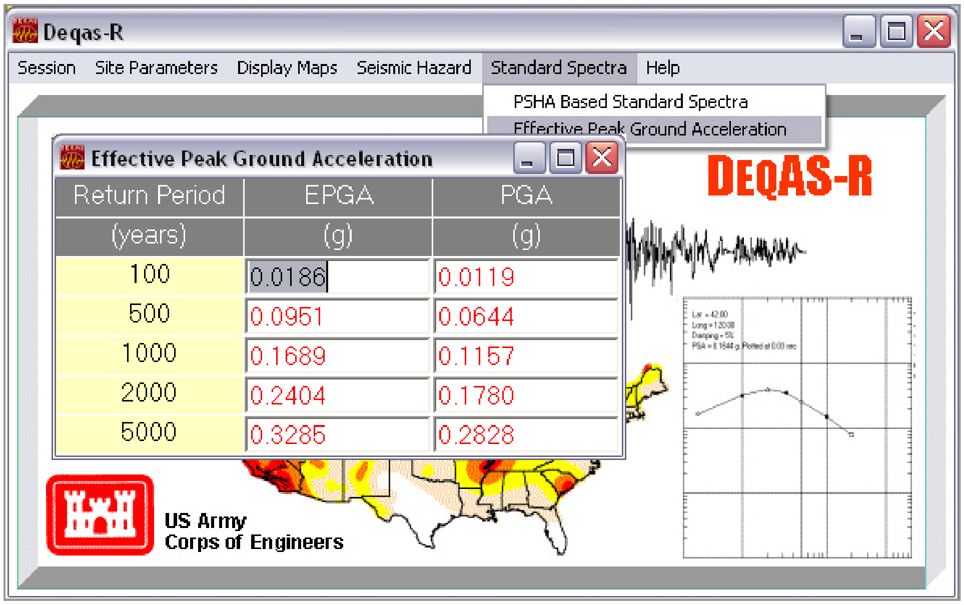


Figure 13. EPGA values for different return periods

For reference purposes, the program also outputs the PGA values corresponding to the required return periods. However, it must be considered that these PGA values are only available for the default site class (firm rock). On the other hand, the EPGA values are calculated as a function of the short-period spectral value modified by site conditions.

SUMMARY: This CHETN describes the development of standard horizontal and vertical response spectra for preliminary design and evaluation of civil works projects. It also addresses the determination of the effective peak ground acceleration values, which are required for seismic stability analysis. Several examples are provided to illustrate the use of the program DEQAS-R.

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